from manufacturers and users. There is no standard evaluation procedure for these materials.

All of the SDHPT districts in Texas were surveyed to determine their experience and evaluation of rapid-setting repair materials. Quantities of each repair material used per year were obtained. Evaluations of each material were made on the basis of types of repair, cost, climatic conditions, durability, bond to concrete, and appearance. Considerable variation was noted for the 27 materials reported.

Other selected states were surveyed to determine their current experience. Six of the eight states responding listed specific materials that were currently being used. Three states provided an evaluation similar to that provided by the SDHPT districts.

The SDHPT districts provided a priority order for characteristics and mechanical properties. Setting time, performance (durability), and working time were ranked as the top three characteristics, whereas bond strength to concrete, flexural strength, and shrinkage were rated the top three mechanical properties.

The survey of the other states indicated performance (durability); ease of mixing, placing, and finishing; and cost as the top three characteristics. Bond strength to concrete, compressive strength, and shrinkage were given as the top mechanical properties.

RECOMMENDATIONS

It is recommended that further research be conducted to establish appropriate evaluation procedures for rapid-setting repair materials, evaluate the most common materials, and determine the field test performance of different types of repairs.

ACKNOWLEDGMENT

We are pleased to acknowledge the combined efforts and support of the Center for Transportation Research at the University of Texas at Austin and the Texas State Department of Highways and Public Transportation in cooperation with FHWA, U.S. Department of Transportation.

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Publication of this paper sponsored by Committee on Pavement Maintenance.

Design of Polymer-Concrete Runway Repairs

B. FRANK McCULLOUGH, A.H. MEYER, AND D.W. FOWLER

Portland-cement-concrete airfield pavements with polymer-concrete (PC) repairs were analytically modeled to develop design criteria for determining the required repair thickness. A previously developed computer program for analyzing discontinuous orthotropic plates and pavement slabs was used to analyze the pavement. Two representative aircraft, the F-4 and the C-141, were used. Different repair sizes, support values, and runway thicknesses were tested. A sensitivity analysis was performed to determine which variables have the greatest effect on the stresses. For the purpose of developing design charts, the critical positions of the wheel loads for the different size repairs were found. The magnitude of the existing runway support (K-value) outside the repair section was found to have little effect on the stresses in the PC repair, although the existing runway thickness did. Because of the emergency nature of the repairs, the repair support values and thicknesses may be significantly different from those for the existing pavement. Consequently, these values have a significant impact on the repair results. Design charts were prepared that give the flexural stress as a function of repair thickness for three repair sizes, two repair support values, and two runway thicknesses. The allowable stress level for the polymer concrete has been reduced for the number of loading repetitions.

The U.S. Air Force, through the University of Texas, has recently studied the rapid repair of runways by using polymer-concrete (PC) materials (1). In some cases a section of a runway can be partitioned off and rapid repairs made so that the field can continue to serve its functional purposes. The results of this study are believed to be applicable to all runway types and thus the information is presented to add to the status of knowledge. In this paper the primary concern is the design aspects; for the material properties, see the papers by Meyer et al. and Fowler et al. in this Record.

Polymer concrete has been shown to be an effective material for rapid repair of bridge decks, pavements, and runways. PC materials consist of aggregate with a polymer binder instead of portland cement. Polymer concrete made with methyl methacrylate develops a strength of 6,000 psi in 1 hr or less (almost the ultimate value), is more ductile than portland-cement concrete (PCC), and bonds well to normal concrete.

In this paper the mechanistic modeling of concrete pavements with PC repairs is described to develop criteria for determining repair thicknesses. The behavior of the repairs was predicted for a wide range of support and loading conditions expected at North Atlantic Treaty Organization (NATO) bases in Europe. Then field tests were made at Tyndall Air Force Base in Florida to experimentally verify the boundary conditions on the charts. Design charts are presented for quickly determining the thickness of repairs required for the anticipated conditions.

It is essential in any analytical approach that techniques be used to properly model the load, geometry, and material properties to reliably predict the stresses in the pavement. In this study the SLAB 49 program developed by Matlock and Hudson for problems such as this (2) was used for developing the design charts.

Figure 1 presents a plan view and a longitudinal cross section of a runway pavement slab containing a repair section. A typical slab, 24 x 36 ft, was selected for study. In previous studies this size has been found to be adequate for studying the stress and deflection distribution for aircraft loadings. In this study the F-4 and C-141 were selected as the representative aircraft.

For the PC patches, three sizes were selected: 5 x 5 ft, 17 x 17 ft, and 24 x 36 ft. A preliminary study indicated that the shape would have only a minor influence on the stresses (less than 1 percent) except for extreme conditions. The thickness of the PC repair ranged from 5 to 10 in. in 0.5-in. increments. The support values selected were 50, 100, 200, and 300 pci; 50 pci represents a backfill with a minimum compaction. These values were guidelines provided by the U.S. Air Force based on previous testing.

For the existing PCC pavement, thicknesses of 8, 12, and 16 in. were considered. The support values selected were 100, 300, and 500 pci.

The following parameters were held constant in the study based on extensive laboratory tests conducted as a part of this study and reported elsewhere (1, paper by Meyer et al. in this Record):

$$E_{PC} = 2 \times 10^6 \text{ psi} \tag{1}$$

$$\nu_{PC} = 0.30 \tag{2}$$

$$E_{PCC} = 4 \times 10^6 \text{ psi} \tag{3}$$

$$\nu_{PCC} = 0.15 \tag{4}$$

where E_{PC} and E_{PCC} are the moduli of polymer concrete and portland-cement concrete, respectively, and ν_{PC} and ν_{PCC} are the Poisson ratios for the same materials.

Figure 1. Runway repair plan and section.

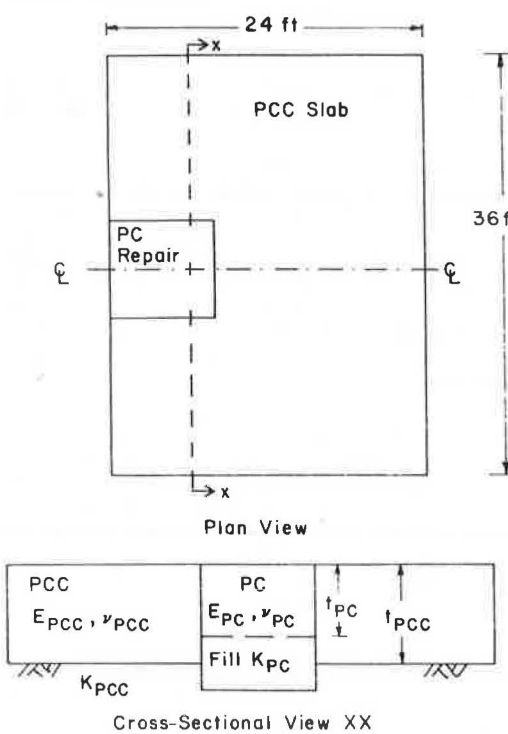


Figure 2 shows a footprint of the gear configurations of both aircraft with the weights and the tire pressures. Previous investigations have indicated that the stress will vary depending on the placement of the wheel relative to the edge, corner, and interior (3). Figure 3 shows the slab loading conditions expected in the field for the various aircraft types and repair conditions. Basically the conditions range from an interior location, represented by position 1, to a corner-edge condition, repre-

Figure 2. Aircraft load and gear configuration.

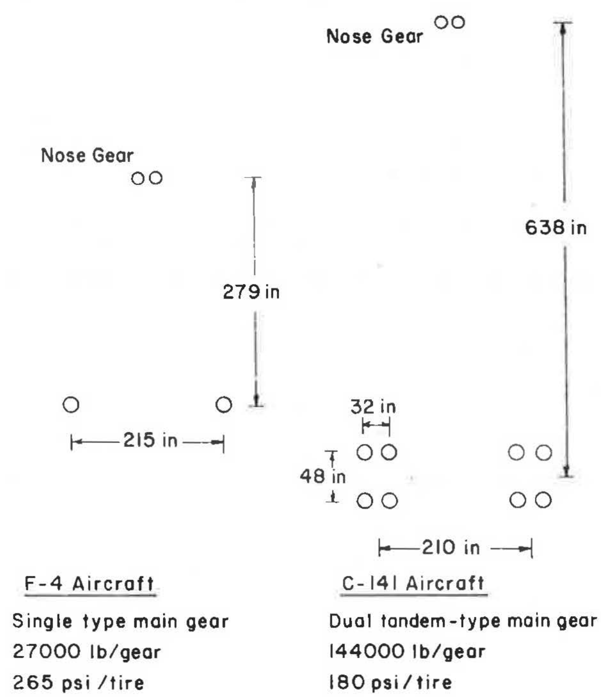
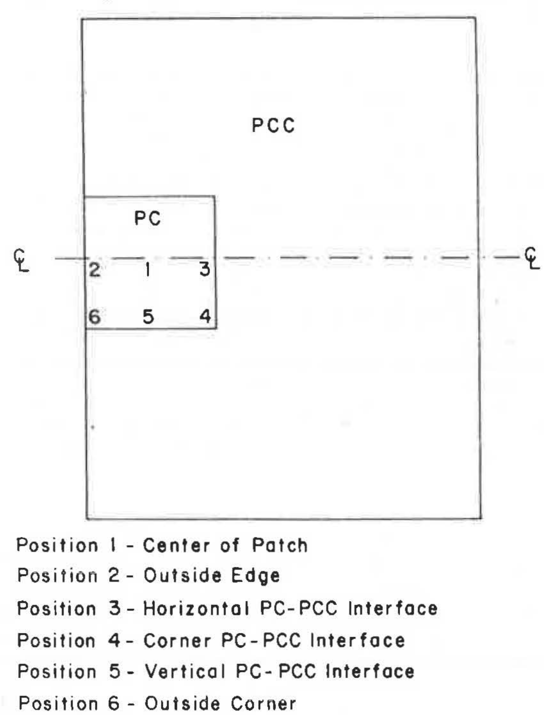


Figure 3. Horizontal load position for F-4 and C-141 aircraft.



sented by position 6. The maximum flexural stress beneath the gear must be determined for all the factors considered to ascertain the critical condition. For the C-141 aircraft, the load placements for positions 1, 2, and 3 were varied slightly, as shown in Figure 4, because the tire-gear configuration was tandem. For one placement the front wheels were placed directly on the repair-section centerline, and for the other position the center of the gear was placed at the center of the repair, as shown in Figure 4.

SENSITIVITY STUDY OF VARIABLES

The nature of this study presented a wide range of conditions for investigation, and as the study progressed, it was obvious that some of the variables had no significant influence on the results. These factors are discussed briefly to provide background for the reasons that some variables are not considered in the analysis.

The presence or absence of the nose gear did not significantly influence the maximum stress conditions; this may be attributed to the wheel-base distances of 279 and 636 in. for the F-4 and the C-141, respectively. For most of the calculations, the nose gear was not considered. In addition, the maximum stress was not influenced by the adjacent gear because the wheel-tread distances were 210 and 215 in., respectively. The stresses, given in the next section, result from studies on one gear and thus would not be different if the entire configuration had been considered.

Considering the horizontal position of the gear, it was found (Figure 3) that positions 1, 2, and 3 were critical, whereas the other positions were less critical, because they received support from the stiffness of the surrounding PCC. Therefore the information reported in later sections is relative to positions 1, 2, and 3.

In the case of the 5 x 5-ft PC repair, positions 1, 2, and 3 were close together; subsequently only position 2 (edge) was considered, because it was the most critical. In the case of the 17 x 17-ft PC repair and the 24 x 36-ft PC repair, the study showed that position 3 had a low value of flexural stress compared with positions 1 and 2 for the F-4 aircraft load. Thus, this position was considered to have relatively little influence on the life of the repair. The loading with the C-141 showed that position 3 gave a higher stress than position 1. This is attributed to the wide load distribution of the C-141 main gear, which, unlike the F-4 main gear, is not influenced by the surrounding PCC. Although flexural stresses were found for position 1 that were not significantly lower than those obtained for position 3, it was decided that the design for position 3 would satisfy the condition of position 1.

In summary, only position 2 (representing the edge condition) and position 1 (representing the interior condition) were considered significant for the F-4 aircraft. Only position 2 (representing edge condition) and position 3 (representing the interior condition) were considered significant for the C-141.

For the C-141 aircraft, which has a dual-tandem gear, the two positions shown in Figure 4 were analyzed and the results indicated that loading the gear tires on the center of the repair gave the most critical stresses. This position was used for further analysis. Another problem investigated for the C-141 dual-tandem gear was the location of the maximum flexural stresses, which were found to occur directly under the tire.

The results given in Figures 5 and 6 indicate that varying the existing runway support has no influence on the repair section flexural stresses. The runway support was then fixed at 300 pci, which is slightly above the average (250 pci) existing at many bases. Although the 300 pci does not influence the results, it permits the user to consider repair support K_{PC}'s up to 300 pci, because of the primary assumption, i.e., $K_{repair} \leq K_{runway}$.

For a 17 x 17-ft repair, varying the existing runway thickness did not influence the flexural stresses in the repair section significantly (Figure

Figure 4. C-141 aircraft vertical gear position.

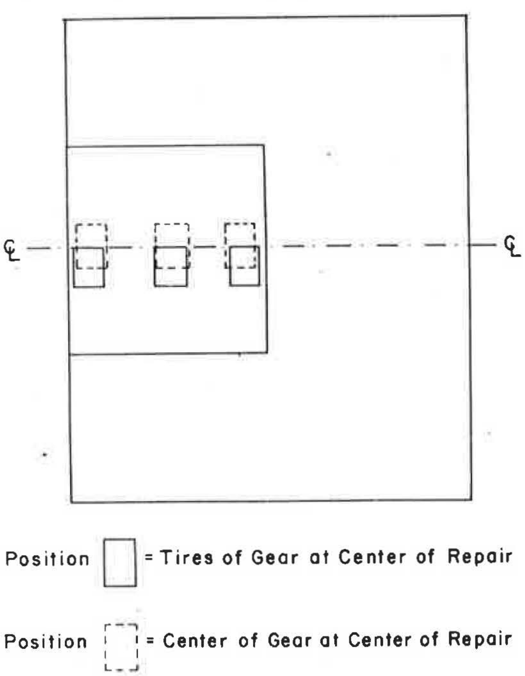
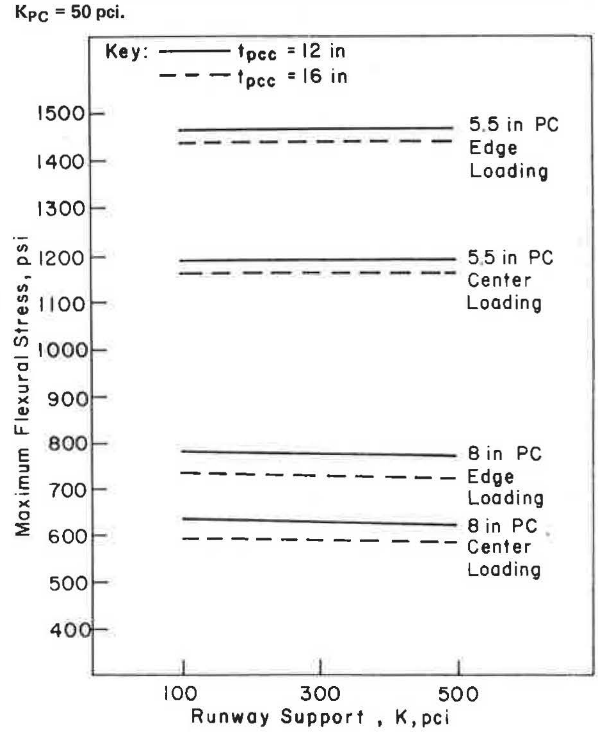


Figure 5. Stress versus runway support for F-4 loading, 5 x 4.5-ft repair, and K_{PC} = 50 pci.



7). The runway thickness was then fixed at 12 in., because this thickness represents a typical thickness encountered in the field and does not influence the results. For a 5 x 5-ft repair, however, the runway thickness has a definite influence. The values of 12 and 16 in. were used to represent thin and thick pavements, respectively, whereas 8 in. was rejected because high stresses were obtained by loading an 8-in. PCC slab, which indicated that the runway was underdesigned. The repair support has an influence on the results, and the values of 50 pci and 300 pci were selected as representing the extremes (poor and strong support).

The maximum stresses resulting from all conditions where K_{PC} = 300 pci and position 2 (edge) was loaded were plotted, and the boundaries of the stress envelopes for the F-4 and the C-141 are shown in Figure 8. Because the range of stress was small, only the upper boundary for the F-4 and the C-141 was used to represent the edge loading; K_{PC} = 300 pci for all conditions, which reduced the scope of analysis.

DESIGN CHARTS

After the sensitivity study had been completed, design charts were prepared containing only the significant variables as defined by the sensitivity study. Figures 9 through 12 are design charts that present the maximum flexural stress for the repair section in terms of the PC repair depth for a range of conditions. On the charts, qualitative variables are used, whereas the previous information has been developed in terms of quantitative factors. The qualitative factors are as follows:

Small repair size: 25 to 299 ft²,
Large repair size: 300 to 999 ft²,
Major replacement: 1,000 ft² or greater,
Strong repair support: 300 pci or more,
Poor repair support: 50 pci,
Thick existing runway: 16 in. thick, and
Thin existing runway: 12 in. thick.

Figures 9 and 10 present the maximum flexural stress in polymer concrete versus the PC repaired-

Figure 6. Maximum flexural stress versus runway support for C-141 loading and 5 x 4.5-ft repair.

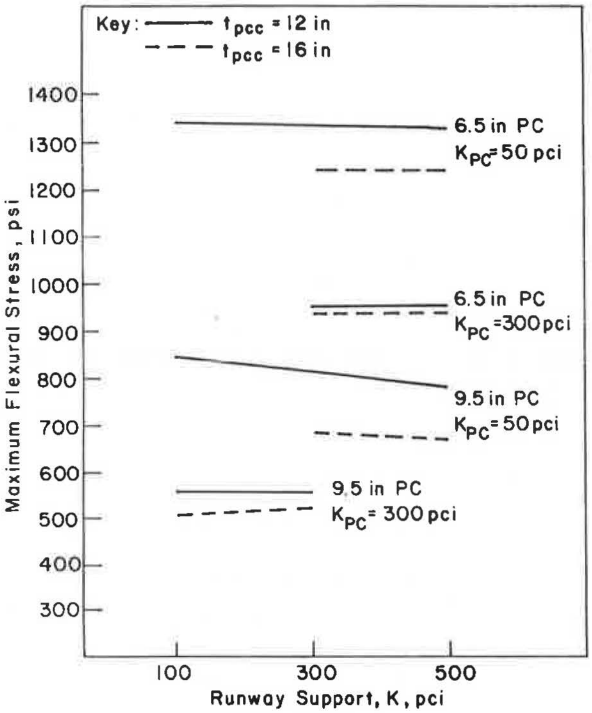


Figure 7. Maximum flexural stress versus runway thickness for 17 x 17-ft repair and C-141 aircraft.

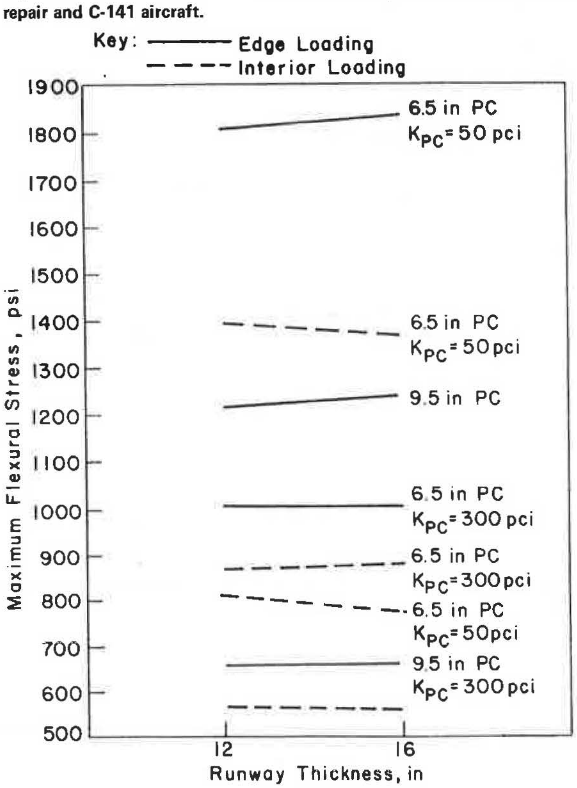


Figure 8. Flexural stress versus PC depth for edge loading and K_{PC} = 300 pci.

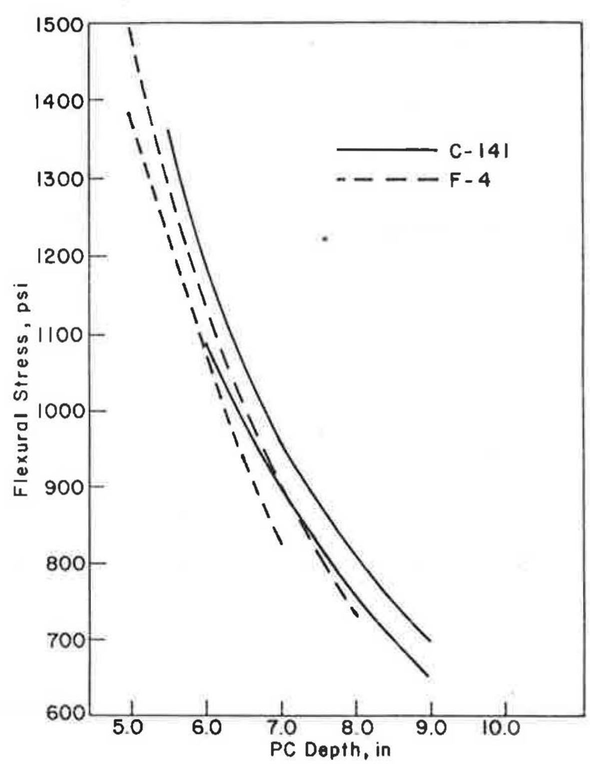


Figure 9. PC thickness design chart for F-4 aircraft and edge loading.

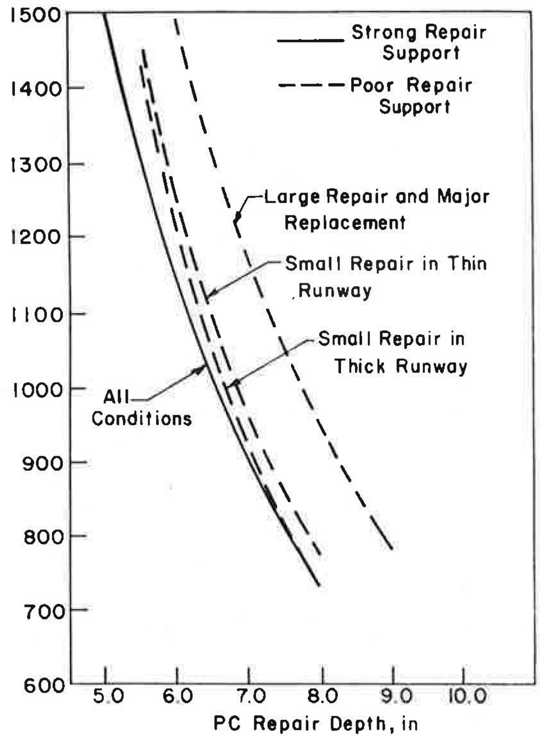


Figure 11. PC thickness design chart for C-141 aircraft and edge loading.

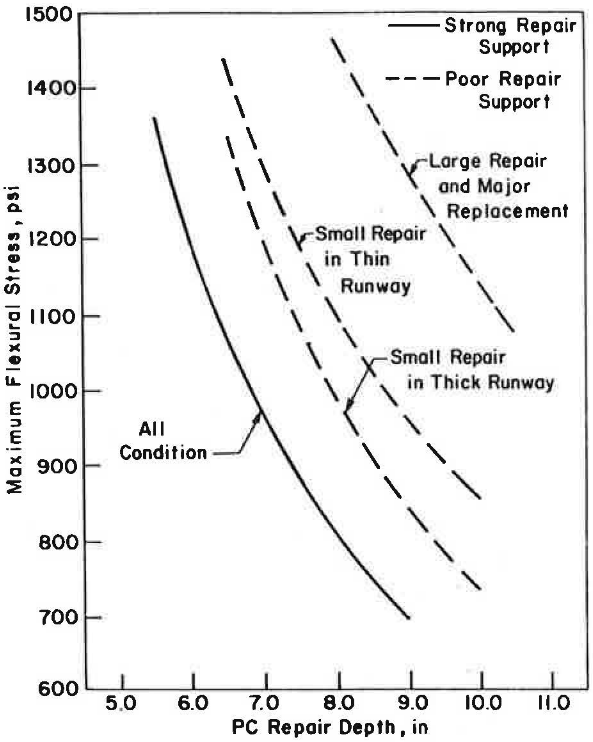


Figure 10. PC thickness design chart for F-4 aircraft and interior loading.

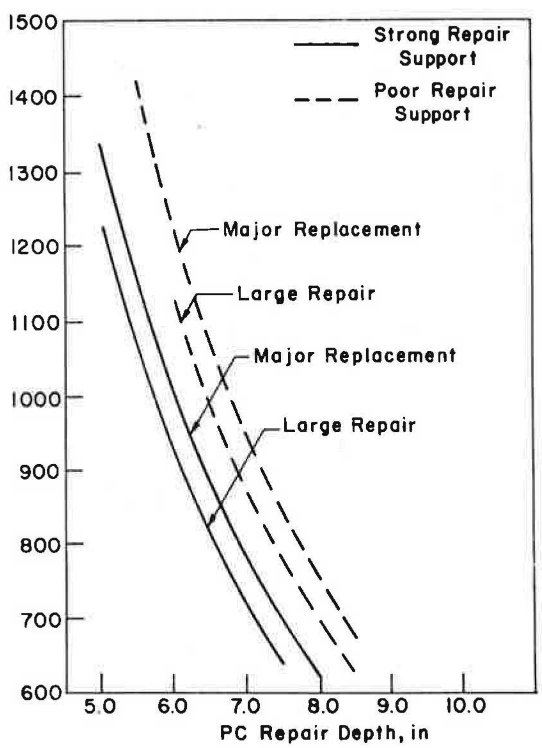
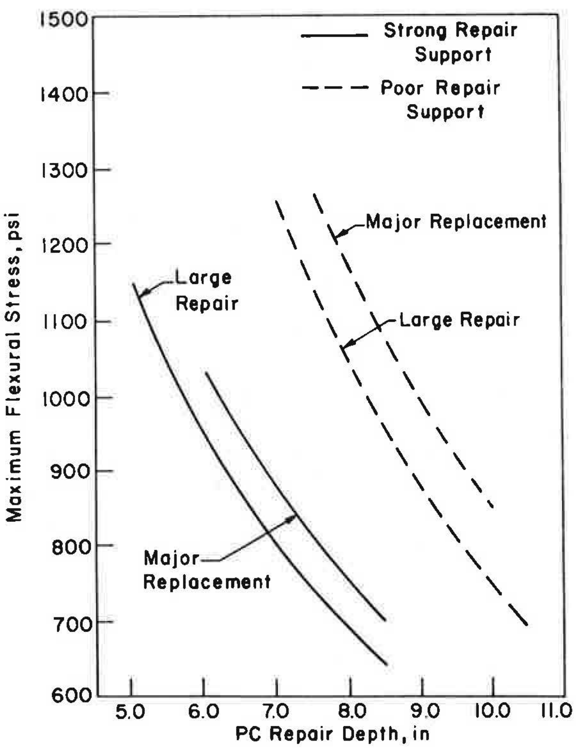


Figure 12. PC thickness design chart for C-141 aircraft and interior loading.



section thickness for the F-4 aircraft for edge and interior loading, respectively. Figures 11 and 12 give the same information for the C-141 aircraft for the edge and interior loading, respectively.

For simple use of the charts, only the edge loading should be considered for the small repairs, whereas for larger repairs and major replacement both edge and interior loading conditions should be considered. In using the chart, the value of the repair support may be interpolated. For the repair size, a size is determined and then the range that encompasses the appropriate figure is found. For example, if the repair area is 225 ft², the user would select the larger repair size for determining the PC thickness. If the repair section encompasses the edge, the edge condition should be selected. The edge condition is selected for longitudinal joints without load transfer or for edge conditions that have been selected because of least-damaged regions. If the repair section is surrounded by the existing pavement, an interior loading condition is used.

The allowable stress level to be used in the equation must be derived as a function of the number of repetitions. Therefore, the fatigue concept is applicable here. The following equation represents a typical fatigue equation that is used for PCC:

$$N = A\,(f/\sigma)^B \tag{5}$$

where

- σ = the stress in the concrete due to the appropriate aircraft loading and other conditions,
- f = the flexural strength of the polymer concrete,
- N = the allowable number of repetitions for the strength and stress conditions, and
- A, B = coefficients for testing specific materials.

This fatigue-equation format has been used for the design of PCC (strain in lieu of stress) and asphalt concrete for a substantial period of time and is felt to be applicable here. The coefficients A and B have not yet been developed for polymer concrete. Because all static tests on polymer concrete have indicated that this concrete is vastly superior to the normal PCC, it is believed that the use of coefficients developed for PCC will be conservative. Therefore, Equation 5 is defined as follows for polymer concrete, based on previous studies:

$$N = 23{,}400\,(f/\sigma)^{3.21} \tag{6}$$

DESIGN PROCEDURE

The following is a sequential procedure that may be used to determine the thickness of PC repair:

1. The thickness of the existing concrete pavement and relative applications of each of the two design aircraft (C-141 and F-4) are determined. It is decided what compaction condition is to be used in the field or repair section (e.g., poor or good) and for what length of time design applications are to be applied.
2. The user surveys the repair section and makes qualitative decisions as to small, large, or major repair replacement, and it is decided whether the repair is a free edge (i.e., whether the repair is surrounded by existing pavement) or zero load transfer at a longitudinal joint.

puted for each aircraft type by using the following equation:

$$\sigma = f\,(23{,}440/N)^{0.31} \tag{7}$$

4. The user then determines the PC repair by entering the appropriate value from Figures 9 through 12 to represent the aircraft type and loading condition. The allowable stress from step 3 is entered at the vertical axis projected horizontally to the appropriate repair section and support condition. At the intersection, the line is projected vertically and the thickness is read on the horizontal scale.

CONCLUSIONS

A design procedure for PC repairs for runways has been presented here that was developed for bomb damage repairs, but the concepts are applicable to any emergency repair. The repair was modeled with a computer program with a large number of variables based on aircraft type, size and location of repair, location of wheel on repair, support stiffness, and repair thickness. Based on the computer analysis, design charts are presented to permit the required PC thickness to be determined. The charts were results from the tests in the field and found to model the field conditions (1).

ACKNOWLEDGMENT

We are pleased to acknowledge the combined efforts and support of the Department of Civil Engineering at the University of Texas at Austin and the U.S. Air Force Engineering and Services Center.

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Publication of this paper sponsored by Committee on Pavement Maintenance.